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Comparative Analysis of Different Hybrid Electricity Generating System Configurations for a Remote Community.

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Abstract

This research paper centered on the comparative analysis of different hybrid electricity generating system configurations in rural communities of Iyi Ochioto and Ochima in Ebonyi state, Nigeria, with emphasis on the techno-economic viability of an optimal hybrid energy system. The community average daily electrical load demand was determined to be 451.32Kwh/day with a peak demand of 52.65kW. Analytical methods was used for designing energy resources such as solar, wind, biomass and diesel generator combined with battery storage for optimal sizing of system components. Hybrid Optimization of Multiple Electric Renewables Software (HOMER Pro) was used to carry out simulation and optimization to determine the system performance and techno- economics parameters like Net present cost (NPC), cost of energy (COE), CO2 emission etc. Five different system configurations were analyzed for technical feasibility and economic viability. Results obtained indicated that three of the selected optimal system configurations, Solar-PV/ Diesel –generator/ Biomass/ Battery-Bank (SDBiB), Diesel-generator/ Biomass/ Battery-Bank (DBiB) and Solar-PV/Diesel-generator/Biomass/wind Turbine/Battery-Bank (SDBiWB) had minimal CO2 emission and were the most cost effective and their solutions were preferred. The SDBiB has a net present cost of $503,451.30, cost of energy of $0.2361/ Kwh, RPF of 95.81 % and CO2 emission 6,946 kg/yr. The DBiB had a total NPC of $514,287.00, COE of $0.242/Kwh, RPF 96.1 %, and CO2 emission of 5,613kg/yr while the SDBiWB had a total NPC of $565,864.50.COE $0.266/Kwh, RPF of 96.1 % and CO2 emission of 6,814kg/yr. The outcome of the research can serves as an input to assist power system planners to intensify effort in electric power production through energy mix, especially in the remote location in the country.

Keywords: Diesel-Generator, Power System Planners, Renewable Software, Net Present Cost, Wind Turbine.

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INTRODUCTION

In today's world, access to reliable electricity is paramount to the fulfillment of basic individual and communal need in the society [1]. For any country to achieve tangible progress in technological advancement and economic prosperity, stable and reliable power supply needs to be made available [2]. Adequate access to electrical energy is the lifeline of modern economies, it plays a cogent role in poverty alleviations, reduction in infant mortality, long life expectancy and rapid urbanization in economically emerging countries [3]. The power system in Nigeria is characterized by a lot of problemsranging from: insufficient generation capacity to meet growing loads, aged transmission and distribution lines occasions by weak financial position of utilities and the inability to recover revenue from low income households, which has made demand for electricity much more than its supply, this has adversely affected the social, economic and commercial activities in the country [4] [5].

The 7th agenda of the 17 listed sustainable development goals (SDGS) of the united nation is the need for all to have access to affordable, reliable, sustainable, and modern energy [6]. Therefore, the provision of universal access to electricity is the ultimate agenda of many governments all over the world because without access to electricity the pathway out of poverty is narrow and long [7].

Nigeria enormous and perennial electricity problems is hindering its development,many citizens living in the urban center have gained access to national grid,while access rate in rural and remote areas have been very slow, notwithstanding the availability of vast natural energy resources ranging from abundant gas to renewable energy sources [8][9].

In other to achieve stable, reliable, affordable and eco-friendly electricity supply, especially in rural or remote communities, the abundant stock of untapped renewable energy resources, coupled with availability of land in semi urbanized and rural communities, can be harnessed and mixed with the non- renewable resources in different configuration of hybrid electricity generating system for community level [10].

This study intends to explore the potential for hybrid electricity generating systems with different configurations in the study area communities (IyiOchioto and Ochima) in Igbo-Etiti Local Government area, Enugu state, integrating renewable energy resources with traditional fossil fuel sources to enhance energy security, reduce carbon emissions, and promote economic sustainability.

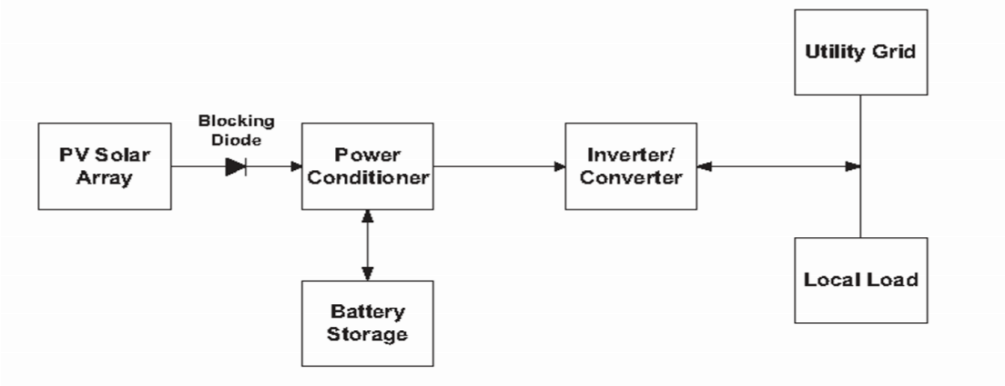
Related Works

Inefficiencies in the generation, distribution and human activities towards depletion of fossils fuel resources have made diversification into renewable and renewable energy mix inevitable [13]. The primary issue addressed in this research is the over reliance on fossil fuels for electricity production in rural communities. This over dependence is accompanied with short comings such as: environmental degradation, greenhouse gas emissions, and economic vulnerabilities due to fluctuating oil prices. In addition, the existing energy infrastructure in most remote communities often struggles to meet the growing demand, leading to frequent power outages and unreliable energy supply [14]. Transitioning to a more sustainable energy system is essential for the long-term economic and environmental health of the community. Nigeria is known to be the most pupulated country in Africa, with only 40% of the entire country's total population connected to the national power grid [15].

The remote and rural communities are often the worst victims as they are rarely connected to the central electricity grid [16]. Due to the intermittent nature of renewable energy resources, penetration of renewable energy system to replace some portion of energy produced by diesel

generator energy is good approach to be considered.In order achieve a better overall power supply pattern, the diesel generator can be used for operation when the renewable sources fail to satisfy the load, and when the battery storage is depleted [17]. Application of hybrid energy systems of different configurations are of increasing interest because a well -managed hybrid electricity generating system can achieve lifetime fuel savings, while ensuring reliable and cost effective electricity supply [18].

Figure 1 and Figure 2 are Block diagram of Solar PV system fundamental and Schematic diagram of wind turbine generator respectively.



.Figure 1: Block Diagram of Solar PV System Fundamental

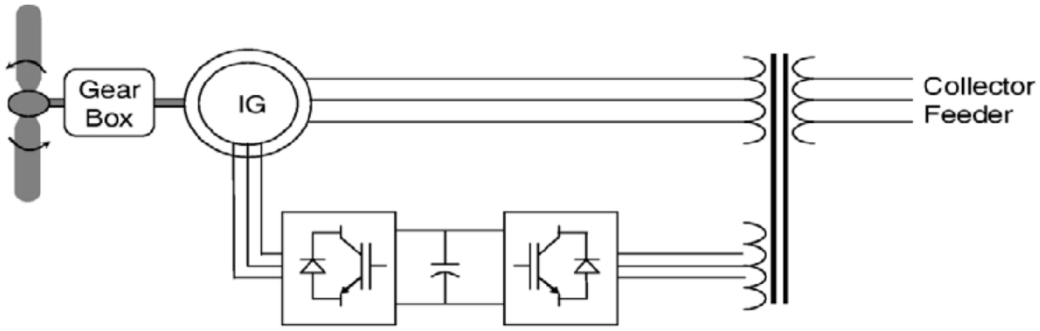


Figure 2: Schematic Diagram of WindTurbine Generator

METHODOLOGY

This study is a comparative analysis of hybrid energy generating system configurations for atypical rural communities. Deterministic method and mathematical modelling was employed for design and optimal sizing of the systems. The simulation and optimization tool used is Hybrid Optimization Multiple Energy Resources (HOMER) software. Climatic condition data of the study community area was used to achieve the optimal system design. The research methodology steps used are summarized as shown in Figure 3.

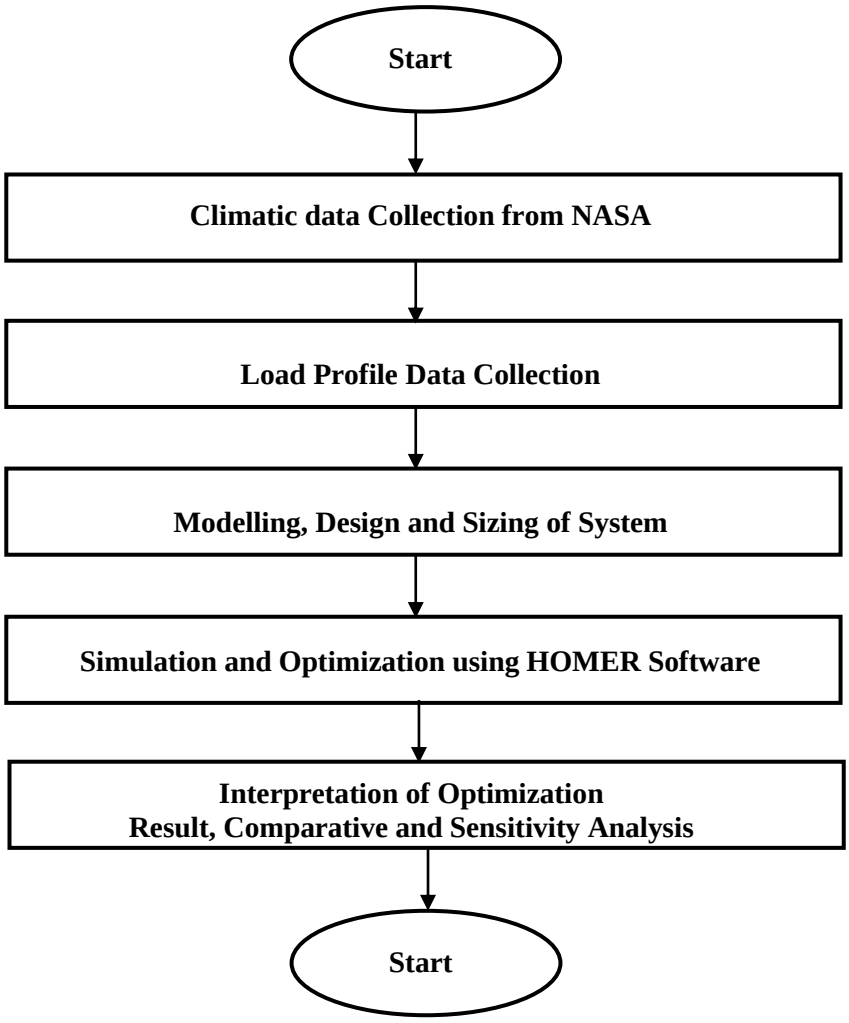


Figure 3: Flow Diagram of the Study Process

- **Study Location**

Iyi Ochioto and Ochioma are communities in Igbo-Etiti LGA, Enugu State, Nigeria. The communities lies between latitude $6°48'N\ and\ 53°44'N$, and longitude $7°25\ \ 10°52'E$. The major occupation of the inhabitants of the communities are farming, fishing, trading, small and medium-scale enterprise like barbing, auto mechanics etc. Field survey through a formal interview was used to analyzed the different electrical equipment currently owned by households as well as those they estimate would be owned by them in the future if there is adequate supply of electricity. The study area is estimated to have a total of 144 households, 12 shops, one public primary school, one public secondary school, community general hall, community water project, street light and other light loads.The average daily demand for the study area is estimated to be 451.32 kwh/day with a peak demand of 52.65kW.

- **Study Area Solar Energy Potential**

The solar radiation data used is the monthly average solar global horizontal irradiance data measured in 10 minutes interval over the period of 10years (July, 1984 – June, 1994) using the communities coordinate as depicted in Figure 4. This was obtained from National Aeronautics and Space Administration (NASA) database on 14/11/2024 and considered in the Homer Pro Software as the solar resources input. The clearness index of the study area and their corresponding solar radiation is as shown in Table 1, the clearness index varies from 0.373 to 0.538.

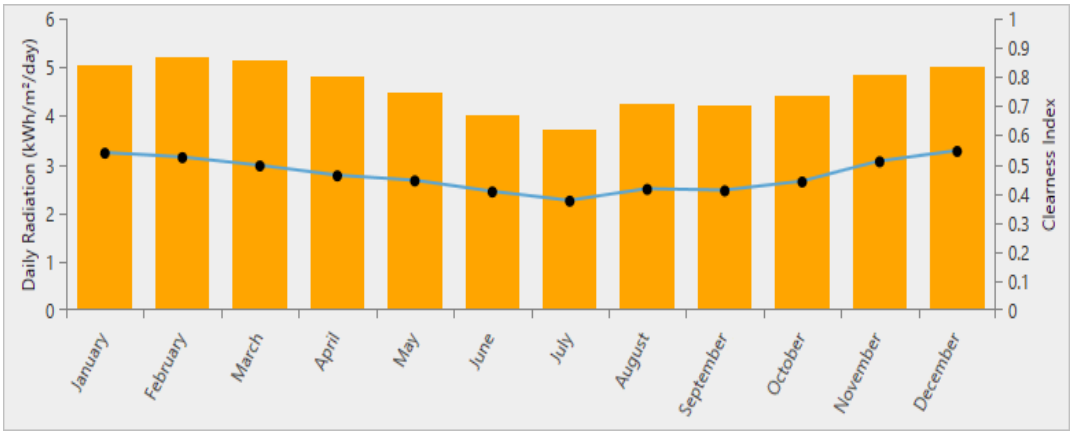


Figure 4: Monthly Solar Radiation and Clearness Index (Homer Pro)

Table 1: 10 year Average Monthly Irradiance and Clearness Index

Month	Average Daily Radiation (kWh/m^2/day)	Clearness Index
January	5.055	0.538
February	5.194	0.523
March	5.130	0.494
April	4.797	0.460
May	4.491	0.443
June	4.009	0.405
July	3.724	0.373
August	4.240	0.414
September	4.222	0.409
October	4.400	0.439
November	4.825	0.509
December	4.998	0.544
Average	4.5904	0.463

Source: NASA Database

- **Study Area Wind Energy Potential**

The speed data used is the data recorded over 24 hours for 10years (1984-1994) by NASA and downloaded from NASA surface meteorology and solar energy database. It was measured at 50 meter above the surface of the earth and 50 meter anemometer height. Table 2 shows the wind speed potential of the study area.

Table 2: 10 – Year Average Monthly Wind Speed

Month	Average Wind Speed m/s
January	2.75
February	2.97
March	2.71
April	2.39
May	2.23
June	2.81
July	3.21
August	3.37
September	2.96
October	2.35

November	2.25
December	2.4
Average	**2.7**

Source: NASA Database

- **Study Area Biomass Resource**

The biomass feedstock material in the study area is rice husk and straws. These are residue of rice processing plant close to the study location environment. One metric tons of rice husk can be supplied to the study area location from the closet rice mills at the cost of 30,000 naira (labour and transportation) which equivalent to $19.93 at the current exchange rate of 1,503.00naira to one US dollar.

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Modeling of Solar PV System

A generic flat plate PV was proposed. HOMER Pro Software optimized the needed capacity to be used. It is assumed that the solar PV modules have a maximum power plant tracking (MPPT) system with associated parameters and values such as capital cost of $4000/kW, replacement cost of $4000/kW, operation/maintenance cost of $50/year, efficiency of 18%, operating temperature of46℃, temperature coefficient of – 0.5, derating factor of 85% and life span of 25 years.

The output of the PV array for each time step will be calculated by HOMER Pro Software uses equation (1):

$$P_{PV} = Y_{PV} F_{PV} \left(\frac{G_T}{G_T ST_C}\right) [1 + \propto_P (T_C - T_G ST_C)] \quad (1)$$

Where;

Y_{PV}: is the rated capacity of the PV array (kW)

F_{PV}: is the PV derating factor (%)

G_T: is the solar radiation incident on the PV array (kW/m^2)

$G_T ST_C$: is the incident radiation at standard test condition (1kW/m^2)

$\propto_P$: is the temperature coefficient of power (%/℃)

T_C: is the PV cell temperature (℃)

$T_C ST_C$: is the PV cell temperature under standard test conditions (25℃)

Modeling of Wind Power System

The instantaneous power output of the wind turbine generator will be calculated by Homer using equation (2)

$$P = C_s C P \rho \pi R^2 V^3 \quad (2)$$

Where;

P: is the power derived from a wind turbine (in watts)

C_S: is the aerodynamic power coefficient = 0.593

C_P: is the coefficient of performance (efficiency factor in percentage).

ρ: is the air density (in kg/m^3)

R: is the blade length (in meters)

V: is the wind speed (in meters per seconds).

The selected wind turbine model has cut in speed of 2.5m/s, rated speed of 12m/s, cut out speed of 30m/s, swept area of 500m^2, height hub of 40m. Installation cost of $30,000/unit and a life span of 25 years.

Modeling of Biomass System

Biomass generator with input ranging from 0 to 50kW was specified in this study, so that HOMER Pro will optimize for the required sizing and most cost effective operating sequence. The biogas generator capital cost is $1500/kW, replacement cost is $1500/kW, operational/maintenance cost is $0.18/operating hour, lifetime is 25,000 hours.

The fuel cost of the biogas generator is determined by HOMER Pro by using the fuel curve equation (3)

$$F = F_0 Y_{gen} + F_1 P_{gen} \quad (3)$$

Where:

F: is the fuel consumption

F_0: is the fuel curve intercept coefficient (kg/hr/kW_{rated}) defined as the no-load consumption of the generator divided by its rated capacity.

F_1: is the fuel curve slope (kg/hr/kW_{output}) defined as the marginal fuel consumption of the generator.

Y_{gen} : is the rated capacity of the generator (kW).

P_{gen} : is the electrical output of the generator (kW).

Battery Model

For energy storage, a generic 12V, lead acid solar battery was selected for this design. The rated capacity 83.4Ah, 90% charge efficiency. 40% depth of discharge, maximum charging current of 16.7A, installation cost of $500/kW, operational/maintenance cost of $40/year and lifetime of 10years, maximum discharge current of 24.3A.

The autonomy of the battery can be determined using equation (4)

$$A_{batt} = \frac{N_{batt}\, V_{nom}\, Q_{nom} \left[\frac{1-q_{min}}{100}\right] \left(^{24h}/_{d}\right)}{L_{prim\ .ave}\,(100Wh/kWh)} \quad (4)$$

Where;

A_{batt} : is the storage battery bank autonomy (hrs)

N_{batt} : is the number of batteries in the storage bank.

V_{nom} : nominal voltage of a single storage (V)

Q_{nom} : is the nominal capacity of a single (Ah)

q_{min} : is the minimum state of charge of the storage bank (%).

$L_{prim\ .ave}$: is the average primary load (kWh/d)

Diesel – Generator Model

In search for space for diesel generator in a combination of 5kW and 20kW in a given interval of 5kW was tested.The price for diesel was set at $1.4per liter, which is dollar equivalent for ₦1,400 price per litre of diesel in Nigeria presently. The initial capital cost of the generator $5,500/kW, operation and maintenance cost of $0.04/hour and the lifespan is 25 years.

Converter Model

For this study, a generic converter power model with capital cost of $400/kW, replacement cost of $400kW, operation/maintenance cost of $0, lifetime of 15years and inverter efficiency of 90% was select

- **Modelling of Different Hybrid Electricity Generating System Configurations**

Modeling of different hybrid electricity generating system configurations is made up of two or more of various system components which consists of solar PV array, wind turbine, diesel

generator, biomass generator, converter and battery banks for optimal sizing of the overall system of the communities estimated load demand of 451.32Kwh per day. The chosen possible configurations in this research are as follows:

i. Solar PV/Diesel – Generator/Biomass/Battery-Bank (SDBiB)
ii. Diesel – Generator/Biomass/Battery – Bank (DBiB).
iii. Solar – PV/Diesel – Generator/Biomass/Wind Turbine/Battery Bank (SDBiWB)
iv. Diesel – Generator/Biomass/Wind Turbine/ Battery – Bank (DBiWB)
v. Solar – PV/Diesel Generator/Battery Bank (SDB)

Figure 5 depicts the schematic diagram of the different hybrid electricity generating system configurations when all the required components are put together.

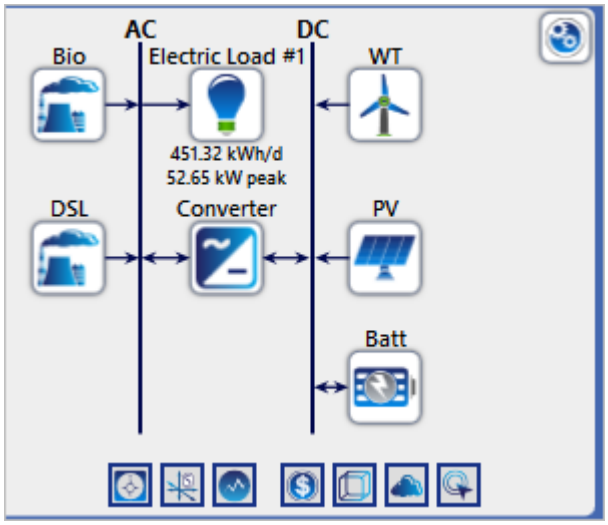


Figure 5: Diagram of Hybrid Electricity Generating System Configurations(Homer Pro)

RESULTS AND DISCUSSION

- **Results of Selected Hybrid Electricity Generating System Configurations**

Bar charts illustrating electrical energy production by each component of the optimal hybrid electricity generating system configurations for cases 1, 2 and 3 are as shown in Figures 6, 7 and 8 respectively. The cases 1, 2 and 3 which are the most cost effective among the chosen five configurations are proposed and discussed in terms of their techno – economics parameters. The optimal system configuration of case 1, Solar PV/Diesel – Generator/Biomass/Battery – Bank (SDBiB) has a reduced the Cost of Energy by 41.3% as when compared to scenario 4 (solar – PV/Diesel – Generator), if chosen as base case. Biomass generation of the study location is high with large part of the load demand (88%) is being supplied by it, attesting to the presence of high biomass renewable energy resources at the study area.

Case 2 has a RPF value of 96.1% as against 95.81% value obtained in case 1, which shows an improvement of 0.3%. It has initial capital of $123,180 as against $125,903 that was obtained in scenario 1, 5,613kg/yr of CO_2 emission as against 6,946kg/yr of CO_2 emission that was gotten in case 1. Case 2 configuration follows the case 1 configuration in terms of COE and NPC.Biomass generation is large supplying 96.1% of the load demand (167,860kwh/yr) to the total energy production of 174,750kwh/yr an increase of 8.10% increase from what biomass generation contributed in scenario 1. Also, in Case 2, the diesel generator contributed 6890kwh/yr (3.94%) to the total energy production, representing a

4.9% reduction from its contribution in case 1 which is the first ranked cost effective optimal HEGS configuration

Case 3 follows cases 1 and 2 in the right order of cost effectiveness with its architecture taking into consideration its RPF 95.9% as against 95.8% of that of scenario 1, with an unmet load of 0.479kwh/yr and capacity shortage of 32.8kwh/yr. The total annual energy production of case 3 is 173,520kWh. Biomass contributed 152,304kWh/year (87.8%) while the wind turbine and Solar PV array contribute (650 kWh/yr) 0.374% and (13,495kWh/yr) 7.78% respectively. These reiterate the good solar and biomass energy potential of the study location. Apart from the higher NPC and COE issues with scenario 3, excess electricity production of 159kWh/yr is also setback compared to 138kWh/hr and 0kWh/yr for cases 1 and 2 respectively. By using COE and NPC as the comparison benchmarks, case 1 is the most suitable for implementation.

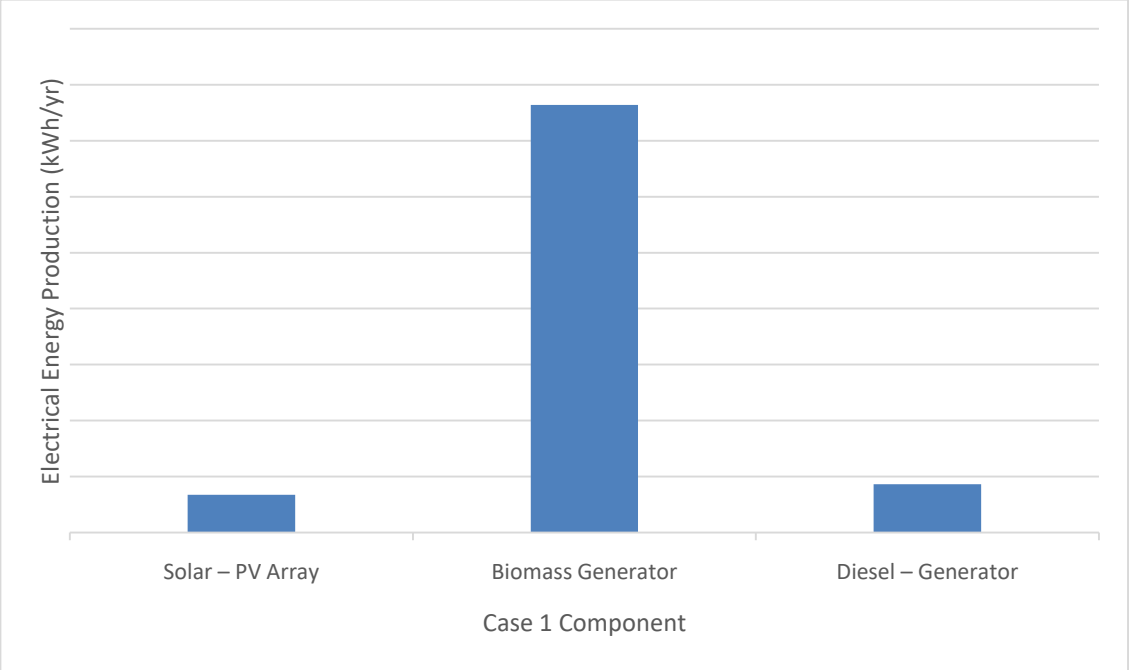


Figure 6: Electrical Energy Production by Each Component of the Optimal HEGS of Case 1

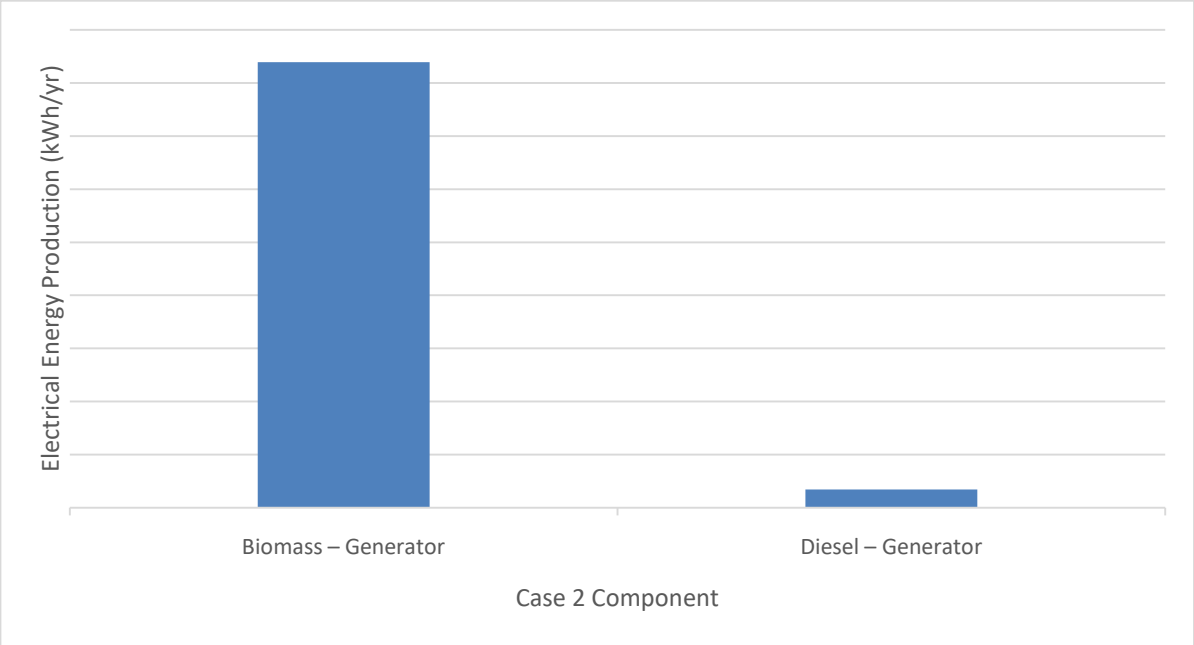


Figure 7: Electrical Energy Production by Each Component of the Optimal HEGS of Case 2

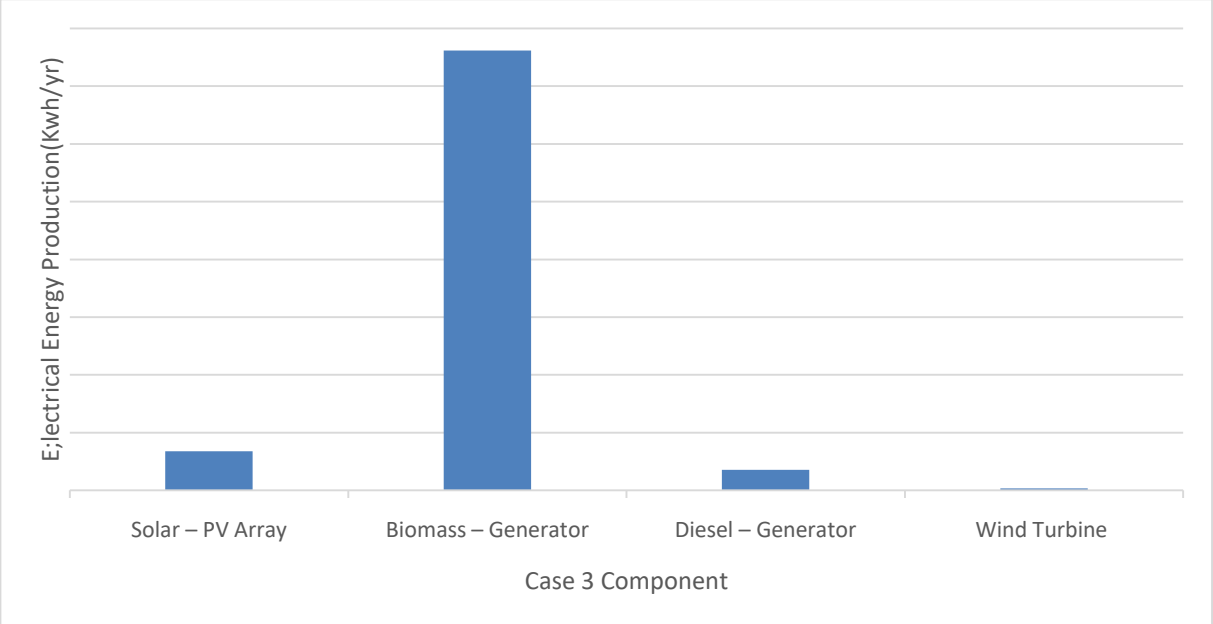


Figure 8: Electrical Energy Production by Each Component of the Optimal HEGS of Case 3

- **Results of Economics Terms of cases 1, 2 and 3 Configurations**

Results of economics terms of the three top-ranked optimal HEGS configuration of the study area is as presented in Table 3. Case 2 have the highest return on investment (54.1%) and the smallest payback time (1.38 yr), it is adjudged the best for implementation if return on investment and payback time is the ultimate consideration.

Table 3: Economics Terms of the Proposed HEGS Optimal System Configuration

Metric	Case 1	Case 2	Case 3
Present Worth ($)	352,723	341,867	290,290
Annual Worth ($/yr)	27,285	26,445	22,455
Return on Investment (%)	53.1	54.1	25.1
Internal Rate of Return (%)	61.8	63.8	30.8
Simple Payback (yr)	1.44	1.38	3.35
Discounted payback (yr)	1.54	1.48	3.69

Conclusion

This study emphasized on the comparative analysis of different hybrid electricity generating system in Iyi Ochioto and Ochima communities in Enugu State. HOMER Pro Software was used to model, simulate and optimize the selected different proposed hybrid electricity generating system configurations for the study area in order to evaluate the techno-economic parameters. Simulation results that were obtained show that the most cost effective optimal system is that of case 1 which is Solar-PV/Diesel – Generator/Biomass/Battery – Bank (SDBiB) configuration with a total NPC of $503,451.30, at 7.36% reduction from what was obtained from case 2 which is Diesel – Generator/Biomass/Battery – Bank (DBiB) configuration and 41.20% reduction from the base case (scenario 5, solar –PV/Diesel – Generator/Battery – Bank) configuration, a COE of $0.236/kWh with 2.48% reduction from scenario 2 and 41.30% reduction from base case of Solar – PV/Diesel – Generator/Battery – Bank Configuration (case 5). Case 2 configuration is, also attractive for implementation which is Diesel – Generator/Biomass/Battery Bank (DBiB). It is also cost effective with total NPC of $514,287.00, COE of $0.242. Scenario 2 configuration has the highest return on investment and smallest payback time.

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